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ANALYTICAL INVESTIGATION OF MAV DYNAMICAL CHARACTERISTICS AND ITS INFLUENCE ON DESIGN

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Abstract

Considered are the questions of stability and controllability of Micro Air Vehicles (MAV) and the mutual dependence of these characteristics and MAV design. Analytical expressions of dynamic characteristics are investigated with respect for MAV. Static and dynamic stability conditions, characteristic frequencies and times are obtained for the most important flight mode (cruise flight) and the influence of MAV design parameters is investigated. Comparison with flight experiment is made.

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Introduction

Micro Air Vehicles (MAVs) differ from larger aircrafts in dimensions, geometric forms and mass distributions. This leads to the conclusion that the dynamical characteristics of MAVs can differ from those of larger ones.

Nowadays the questions of stability and controllability for large aircrafts are investigated well enough, and a set of methods for stability characteristics determination is proposed. But the design of MAVs differs from that of large planes. Usually, MAVs are flying wings (with low aspect ratio), so, most of their "longitudinal" aerodynamic characteristics are defined by the wing. Lateral characteristics are defined by the wing design and fuselage, winglets and other vertical aerodynamical surfaces.

So, one of the purposes of this investigation is to analyze the applicability of these methods for Micro Air Vehicles.

The main questions are the possibility to divide the disturbed motion onto the longitudinal and lateral motions and the possibility to divide longitudinal motion to the short-period motion and long-period (phugoid) motion. It is well known that the possibility of such a separation is defined by aircraft performance.

The next part of questions concerns the applicability of relationships for dynamic characteristics proposed earlier (for example, in [1]) to MAVs.

The last part of questions investigated is connected with influence of MAV parameters on its dynamical characteristics and definition of the recommendations for characteristics improvements through design improvements.

The final aim of this investigation is to obtain the analytical expressions for the stability and controllability conditions of MAV motion as functions of design parameters and to obtain the necessary numerical data for the characteristics of the disturbed motion.

These data are necessary for airplane and autopilot design. For example, it is rather evident that if the period of oscillations for some kind of disturbed motion is smaller than the characteristical time of control surface (or onboard videokamera mechanisms) reaction than this type of disturbed motion must be damped. Moreover, the MAVs not intended for dynamical maneuvers (especially the MAVs intended for the observation purposes) are prompted to be stable.

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For the solution of the problems mentioned above the information about the aerodynamic and dynamic characteristics of low aspect ratio wings is required. Fortunately, in 1970th-90th a set of experiments was carried out to define the static and dynamic characteristics of low aspect ratio wings [2-3], and it is possible to use the data obtained in the MAV analysis. It should be mentioned that from the one hand these results were obtained for rather high Reynolds numbers ($Re \sim 10^6$). But from the other hand the dynamical effects for the flows without separation depend very slightly on the effects of friction.

Conceptual questions

The assumptions for the separation of the disturbed motion on lateral and transversal are [1]:

1. disturbances are small enough,
2. aircraft flies along the straight line without acceleration, without bank and slip,
3. air density is constant (flight altitude change is small enough),
4. aircraft is symmetrical along the vertical plane.

Also it follows from above assumptions that the aircraft must fly at the regimes without flow separation (as separation makes flow asymmetrical).

No more assumptions about the aircraft size and design and the Reynolds & Stroughal numbers and other parameters of similarity have not been made. So, as a conclusion, one can analyze the lateral and transversal motions of MAVs separately at least at rather important case of straight flight without acceleration and without flow separation.

Longitudinal motion

Longitudinal disturbed motion (in Russian tradition) is usually analyzed in the coordinate system where OX axis is collinear to the velocity vector of aircraft, OY axis is perpendicular to OX and lies in the plane of aircraft symmetry and OZ axis is along the right semi-wing.

The values of characteristic scale of time

$$\tau = \frac{2m}{\rho S V_0},$$

and dimensionless aircraft density

$$\mu = \frac{2m}{\rho S L}$$

are required for further investigation (m is mass of MAV, ρ – air density, S – wing area, V_0 – flight velocity, L – wing span).

Let's make the following assumptions.

1. Mach number M is zero and all the coefficient derivatives with respect to M are equal to zero.

2. Thrust vector is directed along the OX axis and is passed through the aircraft center of gravity.

3. Flight altitude is constant.

Under these assumptions the disturbed motion is described by the system of four non-dimensional linearized equations [1]. The solution of this system is in the form of $A\exp(\lambda t/\tau)$, where A is defined by initial conditions and λ is obtained from characteristical equation

$$\lambda^4 + a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0.$$

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In common case λ is complex value. If the real part of λ is negative, then the disturbed motion is damped. This case is required for the stability conditions.

Coefficients of the characteristical equation can be found from formulas [1]

$$\left.\begin{aligned}
a_1 &= C_L{}^{\alpha} + 3C_D - \frac{m_z{}^{\omega z} + m_z{}^{\dot\alpha}}{r_z^2} - \frac{2T^V V_0}{\rho V_0{}^2 S},\\
a_2 &= -\frac{\mu m_z{}^{\alpha} + C_L{}^{\alpha} m_z{}^{\omega z}}{r_z^2} - \frac{m_z{}^{\omega z} + m_z{}^{\alpha}}{r_z^2}\left(2C_D - \frac{2T^V V_0}{\rho V_0{}^2 S}\right) + 2\left(C_L{}^2 + C_L{}^{\alpha} + C_D\left(C_D - \frac{T^V V_0}{\rho V_0{}^2 S}\right) - C_L C_D{}^{\alpha}\right),\\
a_3 &= -2\left(C_L{}^2 + C_L{}^{\alpha} + C_D\left(C_D - \frac{T^V V_0}{\rho V_0{}^2 S}\right) - C_L C_D{}^{\alpha}\right)\frac{m_z{}^{\omega z}}{r_z^2} - 2C_L{}^2\frac{m_z{}^{\dot\alpha}}{r_z^2} - 2\left(C_D - \frac{T^V V_0}{\rho V_0{}^2 S}\right)\frac{\mu m_z{}^{\alpha}}{r_z^2},\\
a_4 &= -2C_L{}^2\frac{m_z{}^{\alpha}}{r_z^2},
\end{aligned}\right\} \quad (1)$$

where $r_z{}^2 = I_{ZZ}/(mb^2)$ is dimensionless MAV radius of inertia for OZ axis, I_{ZZ} – aircraft moment of inertia about an axis OZ, b – mean wing chord, C_L – lift force coefficient, C_D – drag force coefficient, C_i^j – force coefficient derivatives with respect to some variable j, $m_z{}^j$ – moment coefficient derivatives with respect to some variable j, α – angle of attack, ω_z – rotational frequency about an axis OZ, T^v – thrust derivative with respect to V.

The criteria for the stability of motion are

$a_1>0$, $a_2>0$, $a_3>0$, $a_4>0$, $R=a_1a_2a_3-a_1{}^2a_4+a_3{}^2>0$.

The requirement $a_4>0$ assumes that $m_z{}^{\alpha}<0$. This condition can be easily achieved by proper position of the center of gravity (forward of the aerodynamic center (AC)). In [2] the location of aerodynamic center of low aspect ratio wings at low Reynolds numbers was investigated. It was shown that this location depends not only on the aspect ratio but also on the wing shape and the angle of attack. But for further estimations one can assume that AC is located before the 0.25 of mean aerodynamic chord length point.

For the electrical powerplant $2T^V/(\rho V_0 S)$ is negative and of order of $(-C_D)$. So, the condition $a_1>0$ is certainly valid if $m_z{}^{\dot\alpha}<0$ (for the most of cases $m_z{}^{\omega z}<0$). But $m_z{}^{\dot\alpha}$ can change significantly with angle of attack. It was shown in experiments [2] that for the rectangular wings of low aspect ratio the value of $m_z{}^{\omega z} + m_z{}^{\dot\alpha}$ is changing in wide range for $\alpha=10^0$-40^0, and at the angles of attack of 20^0-30^0 even the sign of this expression is changing (so called anti-damping) while for the triangular wings this sum is always negative and increases by its absolute value with the angle of attack increase (see fig. 1). So, for non-rectangular wings at not rather high angles of attack the value of a_1 is positive.

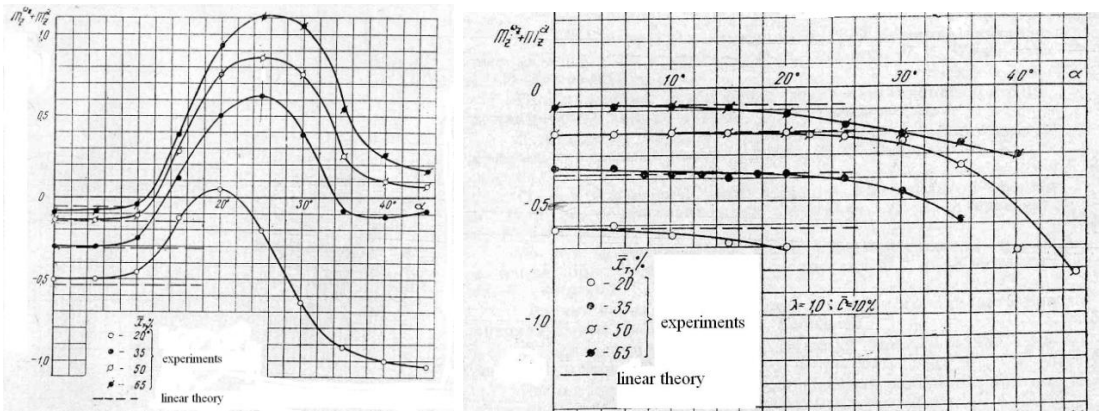

Fig.1. Moment coefficients for rectangular (left) and triangle wing (right) (λ=1, c=10%)

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Also the experiments [2] have shown that for the angles of attack less than 10^0-15^0 the theoretical results of "linear theory" are very close to the experimental points and practically independent of the angle of attack.

Damping coefficient $m_z^{\omega z}$ increases by its absolute value in the case of sweeped wing [1], so the sweeped wings are preferable for MAV dynamical longitudinal stability.

To evaluate the sign of a_2 and a_3 it is required to have some numerical values the coefficients in the expressions (1). Assume that C_L≈0.3-0.5, C_D<0.15, C_{D0}≈0.015-0.02, $m_z^{\omega z}+m_z^{\dot\alpha}$≈-0.5 [2], C_L^{α}≈1.5-2, 4<μ<15, r_z<1, m_z^{α}≈-0.05 (these values are characteristical for MAVs). For these values the coefficients a_2 and a_3 are positive. Also the above assumptions can help to simplify the expressions for a_1, a_2, a_3:

$$a_1 \approx C_L^{\alpha} - \frac{m_z^{\omega z}+m_z^{\dot\alpha}}{r_z^2},$$

$$a_2 \approx -\frac{\mu m_z^{\alpha}+C_L^{\alpha} m_z^{\omega z}}{r_z^2},$$

$$a_3 = -2C_L^{\,2}\frac{m_z^{\dot\alpha}}{r_z^2} - 3C_D\frac{\mu m_z^{\alpha}}{r_z^2}.$$

Now the requirement of a_2>0 is well known condition

$$m_z^{C_L} + \frac{m_z^{\omega z}}{\mu} > 0\,.$$

For the MAVs the second term is not as low as for the larger aircraft. For μ=10 it is about a half of first summand.

In the expression for $R=a_1a_2a_3-a_1^2a_4+a_3^2$ the last summand is lower than others, so one can simplify the requirement in the form of

$$a_2a_3-a_1a_4>0.$$

The next question is the ability to separate the disturbed motion onto short-periodic and long-periodic. One of the ways of roots obtaining described in [1] assumes that there are two pairs of complex conjugated roots, and one pair is much enough comparing to the other with respect to the imagine parts (oscillation frequencies). So, one can obtain the larger roots (in absolute value) from the equation

$$\lambda^2+a_1\lambda+a_2=0$$

and the smaller roots from equation

$$a_2\lambda^2+a_3\lambda+a_4=0.$$

If these roots are really differ significantly, so it is possible to investigate short-period and long-period disturbance separately. The solution of second order equation is well known, so

$$\lambda_{1,2} = \frac{-a_1 \pm i\sqrt{4a_2-a_1^2}}{2}, \lambda_{3,4} = \frac{-a_3 \pm i\sqrt{4a_2a_4-a_3^2}}{2a_2}, \qquad (2)$$

and one can obtain the requirements for the separation:

$$a_1 > \frac{a_3}{a_2}, 4a_2 - a_1^2 > \frac{4a_2a_4-a_3^2}{a_2^2}.$$

From (2) it is easy to analyze the influence of design parameters on the dynamic characteristics. First, the damping of short-period motion can be changed by changing the value of r_z^2. It can be made by changing the location of heavy parts with respect to the center of gravity (CG) without changing the CG location. To increase the damping one must shift the masses closer to the CG. As we can not change the CG location in the wide range,

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we can not also change significantly the value of $m_z^{\omega z} + m_z^{\dot{\alpha}}$ but can change it slightly if necessary (shifting the CG forward increase the damping). One can also increase this sum by the wing sweeping increase.

On the contrary, the damping value and frequency of the phugoid motion is independent of r_Z^2. Damping depends on the value of C_L^2, so for the low velocities the damping is higher (but the characteristic time is longer and the effect is not very strong). The influence of other parameters on the frequency and damping is not so clear. But for the phugoid motion the experience shows that it is enough if the frequency is not too small to have time for reaction from autopilot or operator. The value of damping is recommended to be slightly negative, but even a very small antidumping is acceptable if the period is long enough.
It should be also mentioned that high stability assumes poor controllability. Also, as one can see from fig. 1, wing moment coefficients change with angle of attack, so the controllability characteristics are also changing at high α. This fact must be kept in mind during the autopilot design process.

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Lateral motion

Usually [1] the lateral motion is analyzed in the coordinate system in which OX axis is oriented along the wing chord of airplane, OY axis is perpendicular to OX and lies in the symmetry plane of aircraft and OZ axis is perpendicular to OX and OY (and oriented along the wing length).

The necessary relationships required for lateral motion analysis in the coordinate system defined above are represented below.

If β is sideslip angle, then for the wing moment characteristics are [1]

$$m_x{}^{\beta}{}_W \approx -0.5 C_L{}^{\alpha} \bar{z} \cos^2(\chi)\psi - 0.5\bar{z}\sin(\chi) C_L, \quad (3)$$
$$m_y{}^{\beta}{}_W = -0.06 C_L{}^2 tg(\chi) - \alpha m_x{}^{\beta}{}_W,$$

where $\bar{z}$ is the distance from OX axis to the "semi-wing center of gravity" with respect to semi-wingspan, $0.33 < \bar{z} < 0.5$, χ – wing sweep angle, ψ - wing dihedral.

Torque coefficients due to the rotation for the wing are [1]

$$m_x{}^{\omega x}{}_W = -\frac{\xi}{2}\left(2C_L\alpha + k_i C_L{}^{\alpha}\right),$$
$$m_x{}^{\omega y}{}_W = -\frac{\xi}{2}\left(2 - k_i\right) C_L,$$
$$m_y{}^{\omega x}{}_W = -\xi\left(C_D - C_L\alpha\ \alpha + C_L\left(\frac{C_L{}^{\alpha}}{\pi\lambda} - 1\right)k_i\right),$$
$$m_y{}^{\omega y}{}_W = -\xi\left(C_D - C_L\alpha\ - C_L\left(\frac{C_L{}^{\alpha}}{\pi\lambda} - 1\right)\alpha k_i\right),$$
$$k_i = 0.9(0.5 + 0.033\lambda), \quad (4)$$

where ξ is inertia radius in second power of semi-wing from the symmetry axis with respect to semi-wingspan, $0.33 < \xi < 0.5$.

For low aspect ratio wing [5]

$$C_L{}^{\alpha} = \frac{\pi\lambda}{2},\ C_D = C_{D0} + \frac{2C_L{}^2}{\pi\lambda}. \quad (5)$$

So, last formulas became

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$$m_x{}^{\omega x}{}_W \approx -\frac{\xi}{2} k_i C_L{}^{\alpha},$$

$$m_x{}^{\omega y}{}_W \approx -\frac{\xi}{2} C_L,$$

$$m_y{}^{\omega x}{}_W = -\xi \left(C_{D0}\alpha - 0.5 C_L k_i \right) \approx \frac{\xi}{2} C_L k_i,$$

$$m_y{}^{\omega y}{}_W = -\xi \left(C_{D0} + 0.5 C_L \alpha k_i \right) = -\xi \left(C_{D0} + \frac{C_L{}^2}{\pi\lambda} k_i \right).$$

It should be mentioned that all the torque coefficients of the wing mentioned above are independent of the zero point O at the axis OX of coordinate system OXYZ.

For the vertical tail

$$m_x{}^{\beta}{}_T = k \frac{S_T y_T}{SL} C_Z{}^{\beta}{}_T,$$

$$m_y{}^{\beta}{}_T = k \frac{S_T L_T}{SL} C_Z{}^{\beta}{}_T. \qquad (6)$$

$$m_x{}^{\omega x}{}_T = 2k \frac{S_T}{S} \left(\frac{y_T}{L} \right)^2 C_Z{}^{\beta}{}_T,$$

$$m_y{}^{\omega x}{}_T = 2k \frac{S_T}{S} \frac{y_T}{L} \frac{L_T}{L} C_Z{}^{\beta}{}_T,$$

$$m_x{}^{\omega y}{}_T = 2k \frac{S_T}{S} \frac{y_T}{L} \frac{L_T}{L} C_Z{}^{\beta}{}_T,$$

$$m_y{}^{\omega y}{}_T = 2k \frac{S_T}{S} \left(\frac{L_T}{L} \right)^2 C_Z{}^{\beta}{}_T.$$

$$C_Z{}^{\beta}{}_T < 0,$$

where S_T – vertical tail area, y_T – location of vertical tail aerodynamic center along the axis OY, L_T – location of vertical tail aerodynamic center from the center of gravity, k – flow decrease coefficients on the vertical tail.

These formulas are first of all not very precise and also were obtained for not very low wing aspect ratios and for the classical aircraft design (with vertical tail past the wing). So, some experimental data are required to verify these formulas for our case.

In a set of investigations of G.I.Lukov and V.S. Markina (see, for example, [3]) of low aspect ratio wing with vertical tail and/or tails at various positions along the wing the following facts for the static moment coefficients have been obtained.

1. The absolute value of $m_y{}^{\beta}{}_W$ is rather small in comparison with $m_y{}^{\beta}{}_T$.
2. Up to the angles of attack of 20^0 the value of $C_z{}^{\beta}$ can be assumed as constant.
3. Relationship (6) is in good coincidence with experiment results
4. $m_x{}^{\beta}$ can be assumed as linear with respect to C_L as in (3).

For the isolated vertical tail its value of $C_z{}^{\beta}$ coincides with the theoretical formula (5) with good accuracy. But for the vertical tail on the wing the experimental absolute value of $C_z{}^{\beta}$ is higher than for isolated tail. This fact can be explained by the "ground effect" (the "ground" is the wing plane). If the tail is situated at the axis OX of the wing then the value of "isolated" $C_z{}^{\beta}$ must be multiplied on the coefficient ~1.5. If the tail is situated at the end of the wing then multiplicator is ~1.3.

For further investigations the characteristic "lateral" scale of time

$$\tau_{\perp} = \frac{m}{\rho S V}.$$

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is required.

Dimensionless radii of inertia are

$$r_{XX} = \frac{4I_{XX}}{mL^2}, r_{YY} = \frac{4I_{YY}}{mL^2},$$

where I_{XX} and I_{YY} are inertia moments of airplane about the axes OX and OY. It is assumed that I_{XY}=0.

All torque coefficients below are normalized (assumed to be divided on the appropriate dimensionless inertia radii):

$$\bar{m}_i^{\,q} = \frac{m_i^{\,q}}{r_{ii}}.$$

With the help of the above relationships the characteristical values λ of dimensionless disturbed motion for level flight can be found from the characteristic equation [1]

$$\lambda^4 + a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0,$$

where [1]

$$\begin{aligned}
a_1 &= -\ 0.5C_Z^{\,\beta} + \bar{m}_x^{\,\omega x} + \bar{m}_y^{\,\omega y}\ , \\
a_2 &= 0.5C_Z^{\,\beta}\ \bar{m}_x^{\,\omega x} + \bar{m}_y^{\,\omega y}\ +\ \bar{m}_x^{\,\omega x}\bar{m}_y^{\,\omega y} - \bar{m}_x^{\,\omega y}\bar{m}_y^{\,\omega x}\ - \mu\ \bar{m}_y^{\,\beta} + \bar{m}_x^{\,\beta}\ , \\
a_3 &= -\left\{ \begin{array}{l} 0.5C_Z^{\,\beta}\ \bar{m}_x^{\,\omega x}\bar{m}_y^{\,\omega y} - \bar{m}_x^{\,\omega y}\bar{m}_y^{\,\omega x}\ + \mu\ \bar{m}_x^{\,\beta}\bar{m}_y^{\,\omega x} - \bar{m}_y^{\,\beta}\bar{m}_x^{\,\omega x}\ - \\ -\mu\alpha\ \bar{m}_x^{\,\beta}\bar{m}_y^{\,\omega y} - \bar{m}_y^{\,\beta}\bar{m}_x^{\,\omega y}\ + 0.5\mu C_L\bar{m}_x^{\,\beta} \end{array} \right\}, \\
a_4 &= 0.5\mu C_L\ \bar{m}_x^{\,\beta}\bar{m}_y^{\,\omega y} - \bar{m}_y^{\,\beta}\bar{m}_x^{\,\omega y}\ , \\
C_Z^{\beta} &= C_Z^{\beta}{}_T S_T / S_W.
\end{aligned} \qquad (7)$$

For the most part of cases two roots of the characeristical equation are real and two others are complex conjugate values (these roots are responsible for so-called “Dutch step”).

For the stability, as in previous case, it is required that

$$a_1>0,\ a_2>0,\ a_3>0,\ a_4>0,\ R=a_1a_2a_3-a_1^{\,2}a_4+a_3^{\,2}>0.$$

From (7) one can see that a_1 is always higher than zero.

If a_4<0 then the motion is spirally-unstable, if R<0 then the motion is oscillatory-unstable [1].

Using the relationships for the coefficients and experimental data one can simplify the shape of a_4 for the case of **non-dihedral** wing as shown below

$$a_4 \approx \frac{\mu C_L C_Z^{\,\beta} L_T S_T}{2 r_{XX} r_{YY} L S}\left(\bar{z}\sin\ \chi\ \frac{L_T}{L} - 0.5k\xi\ \ 2 - k_i\ \right)$$

It is evident that the sign of a_4 is defined by the expression in brackets.

From (4), for λ=1 the value of k_i≈0.5. Assuming χ=30^0, L_T/L=0.5, one can obtain that the expression in the brackets of last formula is about -0.1 (i.e. a_4<0) while the first item in the brackets is about +0.1. So, it is rather difficult to obtain a_4>0 for the wing without dihedral.

Wing dihedral can improve this situation. As $m_x^{\,\beta}{}_W$ due to dihedral is independent of C_L, so for small C_L the coefficient a_4 can become positive, but at higher C_L value of a_4 decrease and can become negative.

But it should be noted that even for the negative a_4 its absolute value is small enough for MAV, so the characteristical time is long enough (about 3-10 seconds), and the pilot or autopilot have the possibility to improve the situation.

To evaluate other characteristics of lateral motion let’s simplify characteristic equation coefficients using the experimental data:

$$a_1 \approx -\bar{m}_x^{\,\omega x} - \bar{m}_y^{\,\omega y},$$

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$$a_2 \approx -\mu\bar{m}_x^{\beta} - \mu\bar{m}_y^{\beta},$$
$$a_3 \approx \mu\left(-\bar{m}_y^{\beta}\bar{m}_x^{\omega x} + \frac{C_L}{2}\bar{m}_x^{\beta}\right).$$

The preliminary investigations show that complex roots are rather high by their absolute value comparing with two other. So, as in the case of longitudinal motion, one can find the approximate solution from the equations

$$\lambda^2+a_1\lambda+a_2=0,\ a_2\lambda^2+a_3\lambda+a_4=0.$$

so

$$\lambda_{1,2} = \frac{-a_1 \pm i\sqrt{4a_2 - a_1^2}}{2}, \lambda_{3,4} = \frac{-a_3 \pm \sqrt{a_3^2 - 4a_2a_4}}{2a_2}.$$

It was shown above that the absolute value of one of real roots is small enough. So, the second real root can be estimated as $(-a_3/a_2)$.

Damping coefficient for $\lambda_{1,2}$ increase by absolute value with the radii of inertia decrease.

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Flight experiment

To validate the results obtained the experimental MAV was designed (see fig.2) and made and the set of flight experiments were conducted.

The characteristics of this MAV are: L=0.29m, S=0.0644m^2, V_0=7m/s, m=0.08kg. From this, τ=0.3s, $\mu\approx$8.

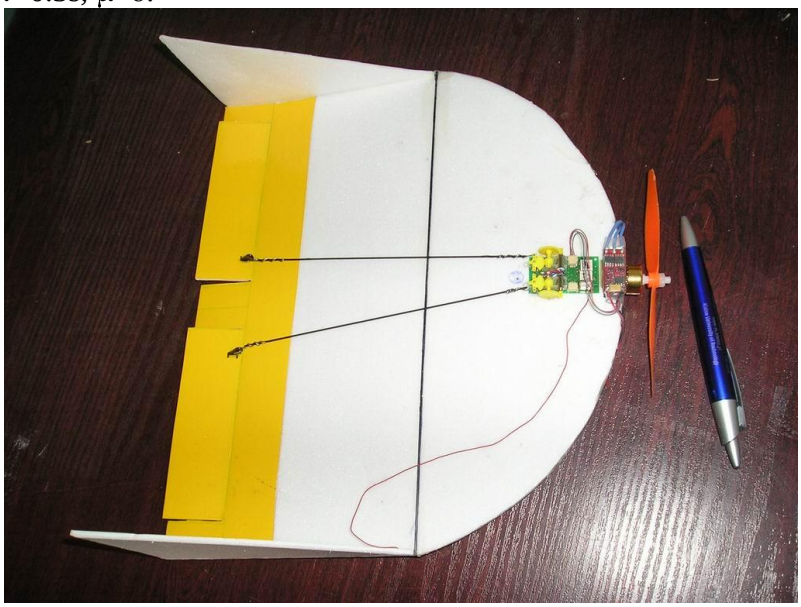

Fig. 2. Experimental aircraft

The aircraft is stable in longitudinal motion. The oscillatory mode of lateral motion is also stable; the period of oscillations is about 0.4s, that coincides with the theoretical result.

As for the spiral mode, pilot can not say confidently if this mode stable or not. This may be explained by the long characteristic time for spiral stability (instability) and atmospheric disturbances.

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Conclusions

1. Equations of MAV disturbed motion can be separated onto the longitudinal and lateral motion.

2. MAV longitudinal motion can be separated onto short-period and long-period (phugoid) motion.

3. Approximate expressions for the disturbed motion characteristics were obtained.

4. Wing sweep is preferable for MAVs with low aspect ratio because of good influence on lateral static stability and longitudinal dynamical stability. Also some wing dihedral is recommended.

5. Decreasing the radii of inertia can be recommended for the increase of MAV stability.

4. Results of flight experiment coincide with theoretical predictions with acceptable accuracy. So, one can use the analytical expressions to predict MAV stability characteristics.

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